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An Assessment of Plant Growth and Soil Properties Using Coal Char and Biochar as a Soil Amendment

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Abstract: Soil degradation due to loss of soil organic carbon is a serious concern in semiarid agroecosystems. Biochar and other organic char products have long been known to increase soil organic carbon. In this study, three-year field observations were carried out on use of coal char (CC) and biochar (BC) as soil amendments in unirrigated semiarid rangeland soil. Coal was pyrolyzed at three different temperatures of 650, 750, and 800 °C to form CC650, CC750, and CC800, respectively, and BC was obtained from a local commercial producer. Manure, CC, and BC were incorporated in soil at 10% (*v*/*v*). Analyses of plant growth (aboveground biomass) and soil properties were performed and compared with the control treatment without char. In all three years, CC applied with manure (CC650M) produced significantly greater grass biomass, by 95, 42, 101%, and BC applied with manure (BCM) increased grass biomass by 89, 39, 52% in 2018, 2019, and 2020, than the controls in the respective years. Soil tests a year after application of char indicated significantly increased soil organic matter (OM) with CC and BC treatments (1.60–2.93%) compared with the control (1.37%). However, further detailed studies are required to investigate CC and BC interactions with soil in unirrigated semiarid rangelands.

Keywords: coal char; biochar; soil amendment; plant growth; soil properties; organic carbon

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1. Introduction

Soil quality is being degraded due to intensive land management practices and increased use of non-carbon (inorganic) fertilizers. The uninterrupted addition of 100% nitrogen fertilizer (urea) causes maximum damage due to increased exchangeable acidity and aluminum in the soil [1]. Continuous use of a high rate of nitrogen, such as that over 1250 kg ha^{-1} in northern Idaho and eastern Washington agricultural soil, has resulted in a decline in soil pH from nearly neutral to less than 6.0 over the past 25 years [2]. Agricultural land is being continuously used for higher productivity to meet the increasing food demands of the rapidly growing population. This intensive use of land decreases nutrients and soil organic matter over time due to the decomposition of OM in the soil. Soil carbon is one of the crucial indicators of soil properties. Organic carbon materials improve soil's chemical, physical, and biological properties by reducing the bulk density of soil, increasing water holding capacity (WHC), and reducing penetration resistance [3]. Adding high-carbon-containing pyrolyzed char materials as a soil amendment could promptly increase soil organic carbon, as they contain more significant amounts of organic carbon. This practice of using high-carbon organic soil amendment materials could provide support for sustainable agricultural practice.

The use of biochar BC, a pyrolyzed plant biomass, as a soil amendment has long been used by indigenous people of the Amazon basin, where they added charcoal to improve soil nutrient holding capacity and crop yield [4–6]. Terra preta soil is evidence of charcoal's historical use to improve soil characteristics and fertility. *Terra preta* is an anthropogenic soil thought to have been created by humans and has a dark brown to black color due to its charcoal content [4]. The dark color of the terra preta soil is attributed to the significant input of char content and fertile soil [7]. Previous studies indicate that terra preta soils have greater cation exchange capacity (CEC), fertility, essential plant nutrients, and stable stored carbon than nearby pedogenically similar soils [8–11].

Similar to BC, CC is a product generated from the pyrolysis of coal that yields porous carbon material with increased surface area and low bulk density. As a soil amendment, CC probably shares many of the characteristics that BC provides to soils, such as increased WHC, soil pH, CEC, and soil organic carbon, and reduced soil tensile strength [12–14]. Low-density CC mixed in soil reduces soil bulk density and may increase the porosity of the soil [15]. Chars are not readily decomposable by soil microorganisms, and are highly resistant to biodegradation [16,17]. This implies that CC and BC, once applied to the soil, could benefit the soil for hundreds or even thousands of years. Agricultural use of CC will put the coal back into the ground as a stable carbon, which is expected to improve soil properties and increase agricultural productivity.

In addition to the OM in CC and BC, negligible quantities of trace elements were found. Some trace elements were volatilized during the pyrolysis process [18,19], and they do not appear to present many environmental risks [20]. During the coal pyrolysis procedure, volatile substances are released in gas and tar, accounting for up to 70% weight loss in the coal, and the remaining material (char) is porous activated carbon [21,22]. Heavy metal-containing soil amendments applied to farmlands can have harmful short-term or long-term effects on the wellbeing of people [23,24]. However, the CC and BC used in this study have very low concentrations of trace elements, which are far below the permissible levels in soil. The reference values for heavy metals allowable in soil have reported in previous studies [25–28], and the heavy metals lab test results of the CC and BC used in this study are presented in Section 3. Moreover, there is concern about polycyclic aromatic hydrocarbons (PAHs) entering the soil with pyrolized products, especially particle-bound PAHs [29]. In 1970, the U.S. Environmental Protection Agency (EPA) suggested a set of 16 PAHs be monitored that are often detected in environmental samples. However, lab tests did not detect any of the U.S. EPA-defined 16 priority PAH concentrations in the CC and BC used in this study. A recent study [30] mentioned that BC-borne PAHs in crops and soils did not pose a significant concern to human health.

CC applied to agricultural land also offers environmental benefits by potentially sequestering carbon in the soil for many years. Currently, coal is primarily used to generate electricity. When coal is burned in coal-fired power plants, carbon returns to the atmosphere as CO_2. Complete combustion of one metric ton of coal generates about 2.84 metric tons of CO_2 [31]. However, turning the coal into CC for soil amendment instead of burning coal at power plants could reduce atmospheric CO_2. Therefore, the use of CC for soil amendment can be an effective way to reduce atmospheric CO_2 concentrations [14]. Different pyrolysis temperatures produce CC with different physical properties and varied carbon percentages in the char [32]. However, until now, there have been no studies on the use of CC produced with different pyrolysis temperatures as a soil amendment, and this is probably one of the first studies of its kind that has used and compared CC and BC simultaneously in the field.

To consider the knowledge gap described above, we established a field experiment to determine the influence of CC, BC, and manure on grass biomass production and soil properties in non-irrigated low-carbon soil. Alongside CC and BC, co-applications with manure treatments were also established. A previous study [33] mentioned that adding manure to the biochar for soil amendment supplies additional organic carbon and nitrogen to the soil, increasing the soil microbial population. We hypothesized that CC, BC, and manure-combined treatments would further enrich nutrients in soil and positively influence aboveground grass biomass yield.

2. Materials and Methods

2.1. Study Area

The field experiment was carried out during the cropping seasons in 2018, 2019, and 2020 at the University of Wyoming's James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC), in Goshen County, Lingle (42.13° N, 104.39° W), WY, USA. The elevation of the study site is 1272 meter (m) and it is located within the semiarid dryland farming environment of the western USA. The site receives 35.56 cm of rainfall and 76.2 cm of snow on average per year and has about 230 sunny days on average in a year [34]. The primary plant growth season of the study site falls between May and August. The soil of the study area has been identified as a fluvisol [35]. The site is 0–3 percent slope and was a floodplain area. The top 15 cm of the soil has 1.4% soil organic matter and a sandy loam soil texture with soil particle composition of 64% sand, 24% silt, and 12% clay. The general soil chemical properties are presented in Table 1. The site was previously a sagebrush (*Artemisia tridentate*) stand burned in the spring of 2017 and planted to forage sorghum in the summer of 2017.

Table 1. Soil properties before using soil additives.

Soil Properties	pH (1:1)	EC (mmhos cm^{-1})	OM (%)	NO_3^-N mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}
	7.9	0.8	1.4	26.6	8.3	186.5

Legend: EC = electrical conductivity, NO_3^-N = nitrate nitrogen, P = phosphorus, K = potassium.

2.2. Soil Amendment Materials

This study used CC and BC alone and co-applied with manure as soil amendments to evaluate plant productivity and soil properties in low-quality, unirrigated sandy loam rangeland soil in a semiarid region. The CC used in this study was prepared by Atlas Carbon LLC, Gillette, WY, USA, with the pyrolysis of the sub-bituminous coal of the Powder River Basin (PRB) at temperatures 650, 750, and 800 °C under oxygen-limiting conditions to produce three different varieties of coal chars: CC650, CC750, and CC800. A biochar producer, High Plains Biochar, Laramie, USA, provided the BC used in the study. Dead wood pine chips and tree barks were pyrolyzed at approximately 650 °C to produce BC. The manure used in this study was a farmyard manure from the SAREC cattle feeding facility, University of Wyoming. No inorganic fertilizers were used in this study.

2.3. Heavy Metals Tests in CC and BC

Heavy metals in CC were tested at Energy Laboratories, Gillette, WY, USA via ICP/ICPMS, CVAA digestion and total metals digestion using reference methods SW6020 [36] and SW7471B [37]. With reduced interference, high precision, wide linear range, and quick analysis speed, ICP-MS is a revolutionary element analysis technology [38]. Heavy metals in BC were tested at Control Laboratories, Watsonville, CA, USA, using the EPA3050B [39]/EPA6020 method for As, Cd, Pb, Zn, Cu, Mn, Cr, Ni, Co, and Se, and the EPA7471B method for Hg. The Fe test was conducted using reference method EPA3050B/EPA6010D [40].

2.4. Soil Amendment Materials Characterization

The moisture content of the CC, BC, and manure was analyzed using the ASTM D1762-84 (105c) method and reported as % wet weight [41]. Ash content in the soil amendment materials was reported as % of total dry mass using the ASTM D 1762-84 method. Organic carbon in the soil amendment materials was reported as % of the total dry mass determined by the dry combust—ASTM D 4373 method [42]. Organic N, ammonium (NH_4^+N), nitrate (NO_3^-N), phosphorous (P), potassium (K), and sulfur (S) concentrations in the soil amendment materials were analyzed on a dry-matter basis and reported in mg kg^{-1}. Dry matter (moisture removed) results allow the direct comparison of nutrients in soil amendment materials.

2.5. Field Experiment and Materials Application

The experiment used a randomized complete block design (RCBD) with three replications for ten treatments, resulting in a total of 30 plots. Each plot measured 37.21 m^2 (6.1 m × 6.1 m). The treatments included were control (no CC, BC, and manure), manure (M), three different-temperature CC only (CC650, CC750, and CC800), three different-temperature CC with manure (CC650M, CC750M, and CC800M), biochar only (BC), and BC with manure (BCM). Soil amendment materials were applied only once at the beginning of the three-year study period (middle of May 2018). Char materials CC and BC were applied to the field at a rate of 10% by volume (v/v), and these treatments corresponded to 17.78 Mg ha^{-1} dry matter of char. Manure-only treatments and manure co-applied with CC and BC were also established to evaluate the results for plant growth and soil properties after application of char with manure. Manure was mixed with CC and BC at a 1:1 ratio 10 days before being applied to the field. For treatments that received both a char product and manure, each product was added at 10% v/v. Immediately after applying soil amendment materials, incorporation was carried out using a 25 cm rototiller to a depth of about 8 cm. Directly following the incorporation, the field was seeded with perennial dryland forage grasses.

2.6. Grass Mix and Biomass Measurement

Five perennial grass species, tall fescue (*Schedonorus arundinaceus*), Russian wild rye (*Psathyrostachys junceus*), pubescent wheatgrass (*Apropyron trichophorum*), hybrid wheatgrass (*Triticum aestivum* × *Elymus trachycaulus*), and crested wheatgrass (*Agropyron cristatum*) were planted in the experimental plots at a rate of 22.42 kg ha^{-1} with equal amounts of seed of each species. Aboveground grass biomass samples were taken manually using a square-meter metal frame in mid-September (four months after sowing) of 2018, 2019, and 2020. Four random grass samples from each treatment were taken using a simple random sampling method, accounting for 12 representatives from three replicates for each treatment type. Grass biomass samples were oven-dried at 65 °C for 72 h and weighed. Mean dry biomasses (g m^{-2}) of mixed grass were compared with the control.

2.7. Soil Sampling and Analysis

Soil sampling from the treatments was initiated a year after the soil amendment materials were applied in the field. Samples were taken to a depth of 15 cm using a JMC Backsaver N-2 Handle soil core from Clements Associates Inc., Newton, IA, USA, in late August 2019 and 2020. Four core soil samples were taken randomly from a plot, kept in a bag, and mixed well to make a composite sample of a plot. The soil samples taken from the field were air-dried and sieved to a size of 0.2 mm to remove rocks and plant debris. Finally, field soil samples were sent for elemental analysis at the Soil, Water, and Plant Testing Laboratory (SWPTL), Colorado State University, USA. Soil samples were analyzed following the laboratory protocols for each elemental analysis in the SWPTL, CSU, USA [43]. The soil's organic matter (OM) was determined using the loss-on-ignition (LOI) method. Soil pH and electrical conductivity (EC) were measured using a 1:1 ratio of air-dried soil–water. Cation exchange capacity (CEC) was determined using Mehlich's barium chloride–triethanolamine method and expressed in milliequivalent of charge per 100 g of dry soil (meq/100 g). The KCL extraction method determined $NO_3^{-}N$, reported in parts per million (mg kg^{-1}) units. Soil P and K were extracted by Olsen's bicarbonate and ammonium acetate (NH_4OAC) methods, respectively, and reported in mg kg^{-1} unit.

2.8. Data Analysis

Analysis of variance (ANOVA) in R (64.4.1.2) followed by post-hoc means separation using Fisher's least significant difference (LSD) test (p < 0.05) was used to examine the significant differences in mean weight of grass biomass and soil properties among the treatments.

3. Results and Discussion

3.1. Heavy Metals in Coal Char and Biochar

None of the test results for different heavy metals in CC and BC exceed the maximum permissible level in soils, except for Zn in biochar (Table 2). Class 1 elements (As, Cd, Hg, and Pb), which are human toxicants [44], were not detected at the reporting level (Cd and Hg) or were found at deficient concentrations (As and Pb, 1.2 mg kg^{-1} and 2 mg kg^{-1}, respectively) in CC. In BC, Hg was not found in the test and the other class 1 elements (As, Cd, and Pb) were at very low concentrations or within permissible levels in the soil. These test results indicate that this study's particular CC and BC are safe to use as soil amendments from a human health perspective. Table 2 shows the reference values for heavy metals in soil and the lab test results for CC and BC.

Table 2. Heavy metals (mg kg^{-1}) tested in CC and BC (Energy laboratory, Gillette, WY and Helena, MT, USA) along with the maximum permissible reference levels in soil.

Heavy Metals	Maximum Permissible Level in Soils (mg kg^{-1})	Levels in Coal Char (mg kg^{-1})	Levels in Biochar (mg kg^{-1})
Arsenic (As)	20	1.2	20
Cadmium (Cd)	3	Nd	2
Lead (Pb)	100	2	7
Zinc (Zn)	300	7	529
Copper (Cu)	100	14	24.3
Manganese (Mn)	2000	22	1.4
Chromium (Cr)	100	5	Na
Nickel (Ni)	50	6	4
Cobalt (Co)	50	2	1
Selenium (Se)	10	Nd	Na
Iron (Fe)	50,000	3650	2.6
Mercury (Hg)	≤0.03	Nd	Na

"Nd" stands for not detected at the reporting limit. "Na" stands for data not available.

3.2. Characterization of CC, BC, and Manure

In the CC and BC lab tests, organic carbon appeared to be very high (>78%) and plant essential nutrient concentrations were reasonably low (Table 3). This suggests that CC and BC need to be applied with nutrient-rich materials such as manure or fertilizers. Table 3 indicates the comparatively greater concentrations of N, P, and K in the manure used in this study than in CC and BC. In addition, manure also contains a good amount of organic carbon, which is decomposed by soil microorganisms, and that process releases nutrients available for plant uptake.

Table 3. Selected physical and chemical properties of soil amendment materials (CSU Soil, Water and Plant Testing Laboratory, Fort Collins, CO, and Control Laboratories, Watsonville, CA, USA).

Properties	Coal Char	Biochar	Manure
Moisture%	4.42	23.8	30.31
Ash%	16.72	8.3	Na
Organic C%	78.86	83.8	42.36
Organic N (mg kg^{-1})	9300	6700	10,100
NH_4^+N (mg kg^{-1})	10	10	60
NO_3^-N (mg kg^{-1})	<10	<10	2500
P (mg kg^{-1})	1700	800	21,200
K (mg kg^{-1})	500	8900	27,700
S (mg kg^{-1})	4700	3900	4500

"Na" stands for data not available.

3.3. Soil Chemical Properties

Soil OM content following CC and BC co-applied with manure treatments was significantly increased compared with the control in 2019 and 2020 (Table 4). In 2019, OM was significantly increased in CC650M, CC750M, and CC850M by 73%, 114%, and 68%, respectively, compared with the control. Moreover, in 2020, CC650M, CC750, CC750M, CC800, CC800M, and BCM treatments increased OM by 72%, 63%, 35%, 42%, 42%, and 31%, respectively, compared with the control. Our results support the prior findings [45] from biochar field studies where soil OM increased following biochar application in a sandy loam soil. Another study [46] reported that total organic carbon in soil was increased by 44, 59, and 215% with 30, 60, and 90 t ha^{-1} biochar application rates, respectively. As shown in Table 4, CEC was significantly greater with CC650M, CC750, CC750M, and CC800M treatments than in the control soil in 2019. Also, in 2020, all three different CC and BC manure-incorporating treatments plus the CC-only treatments CC750 and CC800 resulted in significantly increased CEC compared with the control. This increase in CEC can be attributed to the increase in soil OM with the respective treatments. Soil CEC increases as organic matter increases, and it is used to predict nutrients in the soil and retention of nutrients in the soil [47]. A previous study [48,49] mentioned that biochar can have larger negative charges on the surface ascribed to abiotic oxidation, which creates the phenolic group supporting CEC increase in the soil. Formation of organo minerals due to slow oxidation of char materials could have increased the CEC in the CC- and BC-amended soil [50].

Table 4. Selected soil properties from each treatment.

Year	Treatments	OM (%)	CEC (meq/100 g)	pH (1:1)	EC mmhos cm^{-1}	NO_3^-N	P	K
						………….. mg kg^{-1}	………………..	
2019	Control	1.37 ± 0.3 ^{d}	0.79 ± 0.2 ^{d}	7.83 ± 0.1 ^{ab}	0.8 ± 0.1 ^{ab}	48.00 ± 8 ^{ab}	7.8 ± 1.3 ^{c}	177 ± 17 ^{e}
	M	1.43 ± 0.2 ^{cd}	0.83 ± 0.1 ^{d}	7.97 ± 0.1 ^{a}	0.57 ± 0.1 ^{b}	40.46 ± 0.6 ^{ab}	9.4 ± 0.4 ^{bc}	226 ± 32.9 ^{cde}
	CC650	1.67 ± 0.2 ^{bcd}	1.2 ± 0.1 ^{bcd}	8.00 ± 0.1 ^{a}	0.57 ± 0.2 ^{b}	31.73 ± 9.2 ^{b}	7.57 ± 1.4 ^{c}	184 ± 37.4 ^{de}
	CC650M	**2.37 ± 0.6 ^{ab}**	**1.64 ± 0.1 ^{ab}**	7.90 ± 0.0 ^{ab}	0.70 ± 0.0 ^{b}	37.17 ± 2.3 ^{ab}	**17.8 ± 4.8 ^{ab}**	**342 ± 74.3 ^{a}**
	CC750	2.23 ± 0.3 ^{abcd}	**1.30 ± 0.2 ^{abc}**	7.97 ± 0.0 ^{a}	0.57 ± 0.0 ^{b}	35.6 ± 8.7 ^{b}	7.57 ± 1.1 ^{c}	239 ± 24 ^{bcde}
	CC750M	**2.93 ± 0.4 ^{a}**	**1.70 ± 0.3 ^{a}**	7.9 ± 0.1 ^{ab}	0.63 ± 0.1 ^{b}	33.67 ± 9.5 ^{b}	**20.43 ± 1.8 ^{a}**	**280 ± 21.9 ^{abcd}**
	CC800	2.10 ± 0.3 ^{abcd}	1.22 ± 0.2 ^{bcd}	7.93 ± 0.1 ^{a}	0.67 ± 0.1 ^{b}	41.7 ± 6 ^{ab}	6.73 ± 0.7 ^{c}	193 ± 34.6 ^{de}
	CC800M	**2.30 ± 0.1 ^{abc}**	**1.33 ± 0.1 ^{abc}**	7.7 ± 0.1 ^{b}	1.07 ± 0.3 ^{a}	68.20 ± 18.3 ^{a}	**24.67 ± 5.9 ^{a}**	**322 ± 8.9 ^{abc}**
	BC	1.6 ± 0.1 ^{bcd}	0.93 ± 0.1 ^{cd}	7.87 ± 0.1 ^{ab}	0.73 ± 0.1 ^{ab}	48.77 ± 13.4 ^{ab}	8.37 ± 0.8 ^{c}	248 ± 22 ^{abcde}
	BCM	1.87 ± 0.1 ^{bcd}	1.08 ± 0.1 ^{cd}	8.03 ± 0.0 ^{a}	0.67 ± 0.0 ^{b}	40.13 ± 2.5 ^{ab}	**18.1 ± 4.1 ^{a}**	**327 ± 18.4 ^{ab}**
2020	Control	1.53 ± 0.2 ^{e}	0.89 ± 0.1 ^{e}	7.97 ± 0.1 ^{b}	0.33 ± 0.0 ^{ab}	3.40 ± 1.8 ^{ab}	7.03 ± 0.8 ^{bc}	180.7 ± 6.1 ^{c}
	M	1.73 ± 0.2 ^{cde}	1.01 ± 0.1 ^{cde}	**8.13 ± 0.0 ^{a}**	0.30 ± 0.0 ^{ab}	2.33 ± 1.1 ^{ab}	9.83 ± 1.1 ^{bbc}	232.1 ± 36.4 ^{bc}
	CC650	1.97 ± 0.0 ^{cde}	1.14 ± 0.0 ^{cde}	8.1 ± 0.1 ^{ab}	0.30 ± 0.1 ^{ab}	1.8 ± 1.2 ^{ab}	6.83 ± 1.2 ^{bc}	172.4 ± 17 ^{c}
	CC650M	**2.63 ± 0.2 ^{a}**	**1.53 ± 0.1 ^{a}**	8.03 ± 0.1 ^{ab}	0.33 ± 0.0 ^{ab}	3.87 ± 2.1 ^{ab}	**14.07 ± 1.9 ^{a}**	**311.8 ± 32.9 ^{a}**
	CC750	**2.50 ± 0.2 ^{ab}**	**1.45 ± 0.1 ^{ab}**	8.03 ± 0.0 ^{ab}	0.33 ± 0.0 ^{ab}	2.23 ± 0.9 ^{ab}	7.63 ± 1.3 ^{bc}	234.3 ± 23.3 ^{bc}
	CC750M	**2.07 ± 0.2 ^{bcd}**	**1.2 ± 0.1 ^{bcd}**	8.10 ± 0.0 ^{ab}	0.30 ± 0.0 ^{ab}	1.37 ± 1.3 ^{ab}	10.37 ± 0.5 ^{abc}	241.1 ± 18.5 ^{abc}
	CC800	**2.17 ± 0.1 ^{bc}**	**1.26 ± 0.1 ^{bc}**	8.07 ± 0.0 ^{ab}	0.30 ± 0.0 ^{ab}	1.97 ± 0.8 ^{ab}	5.67 ± 0.1 ^{c}	189.7 ± 31.4 ^{c}
	CC800M	**2.17 ± 0.1 ^{bc}**	**1.26 ± 0.0 ^{bc}**	8.07 ± 0.1 ^{ab}	0.40 ± 0.0 ^{a}	1.93 ± 0.5 ^{ab}	**14.2 ± 2.3 ^{a}**	**291.6 ± 40.6 ^{ab}**
	BC	1.70 ± 0.2 ^{de}	0.99 ± 0.1 ^{de}	8.10 ± 0.0 ^{ab}	0.27 ± 0.1 ^{b}	0.57 ± 0.5 ^{b}	8.57 ± 2.9 ^{abc}	287.7 ± 18.8 ^{bc}
	BCM	**2.0 ± 0.0 ^{cd}**	**1.16 ± 0.0 ^{cd}**	8.10 ^{ab}	0.30 ± 0.0 ^{ab}	5.57 ± 3.1 ^{a}	10.37 ± 3.3 ^{ab}	**330.3 ± 28.3 ^{ab}**

Data are means across three replicates (n = 3) with the associated standard errors. Means followed by the same letters within columns are not statistically significant ($p > 0.05$, Fisher's LSD test). Values in bold represent statistically significant difference compared with the control. M: manure; CC650, CC750, and CC800: coal char produced at 650 °C, 750 °C, and 800 °C pyrolysis temperature, respectively; CC650M, CC750M, and CC800M: manure mixed with the three different CCs; BC: biochar; BCM: BC mixed with manure.

In 2019 and 2020, there was no significant change in soil pH ($p > 0.05$) after applying CC and BC as soil amendments alone or with manure, except for significantly increased pH following M treatment in 2020. The range of soil pH across the treatments was from 7.7 to 8.03 in 2019 and from 7.97 to 8.13 in 2020. Relatively greater pH was detected in 2020 for all treatments compared with 2019. A study [51] reported that soil pH increased by 0.2 and 2.3 from adding rice husk BC and cacao shell BC, respectively, to sandy loam soil. This indicates the nature of BC feedstock impact at different levels in the soil. The materials CC, BC, and manure are alkaline in nature [52], which could have slightly elevated the soil pH over the time of application. Also, organic anions released from the manure could have further contributed to increasing soil pH with the manure-added treatments [48]. The electrical conductivity (EC) of soil did not change significantly ($p > 0.05$) with the CC or BC treatments alone or with manure in comparison to the EC of the control treatment in both years. Soil EC greater than 2 mmhos^{-1}cm is considered slightly saline [53]. However, the soil EC range following treatments in this study ranged from 0.57–1.07 mmhos cm^{-1} in 2019 and from 0.27–0.40 mmhos cm^{-1} in 2020.

The amount of $NO_3{}^-N$ in the soil was found to be not significantly different compared with the control in both cropping years. In 2019, $NO_3{}^-N$ after CC800M treatment (68.20 mg kg^{-1}) was the greatest but not statistically different from the control (48.00 mg kg^{-1}); however, it was found to be greater than CC650 (31.73 mg kg^{-1}), CC750 (35.60 mg kg^{-1}), and CC750M (33.67 mg kg^{-1}). In 2020, $NO_3{}^-N$ concentrations for all treatments were found to be lower than those in 2019, ranging from 0.57 mg kg^{-1} to 5.57 mg kg^{-1}. These decreased $NO_3{}^-N$ concentrations with all treatments in 2020 may be associated with the leaching of nitrate due to the high precipitation in the summer of the previous year (2019). $NO_3{}^-N$ moves easily with water and is affected by the amount of rainfall on the farmland [54]. A heavy rainfall season leads to significant increase in $NO_3{}^-N$ leaching from coarse sandy soil [55].

It was noticed that manure mixed with CC and BC treatments resulted in higher amounts of P and K in soils. In 2019, soil P was found to be significantly greater with CC650M (17.80 mg kg^{-1}), CC750M (20.43 mg kg^{-1}), CC800M (24.67 mg kg^{-1}), and BCM (18.10 mg kg^{-1}) compared with the control (7.80 mg kg^{-1}). Similarly, soil K was also found to be significantly greater with CC650M (342.23 mg kg^{-1}), CC750M (279.63 mg kg^{-1}), CC800M (322.13 mg kg^{-1}), and BCM (326.87 mg kg^{-1}) compared with the control (176.87 mg kg^{-1}). After two years of applying soil amendment materials (2020), soil P was also found to be significantly greater with CC650M (14.07 mg kg^{-1}) and CC800M (14.20 mg kg^{-1}) compared with the control (7.03 mg kg^{-1}). Also, soil K in 2020 was found to be significantly greater with CC650M, CC800M, and BCM with concentrations of 311.77 mg kg^{-1}, 291.55 mg kg^{-1}, and 330.33 mg kg^{-1}, respectively, compared with 180.70 mg kg^{-1} in the control soil. These significantly increased levels of P and K following the treatments where manure was added with CC and BC can be attributed to the high P and K content of the manure (Table 3) used in this study. All char-only and manure-only treatments showed significantly lower soil P and K concentrations in both years. Higher concentrations of soil P and K in char with manure treatments could be due to the effective nutrient holding by CC and BC, which can be associated with the nutrient-holding capacity of the highly porous char materials. This is in agreement with previous research [56] reporting that organic amendments such as manure provide much higher amounts of P and K. The P and K in soil treated with manure alone could have leached from the topsoil due to heavy rainfall in the 2019 growing season, in the absence of char materials that could hold the soil P and K supplied from the manure. Soil samples were taken at the end of August in both years, to a depth of 15 cm from the soil surface, after more significant rainfall in May, June, and July of 2019 (Figure 1). However, a more detailed long-term study is required to investigate the higher concentrations of P and K in soil following treatment with char co-applied with manure.

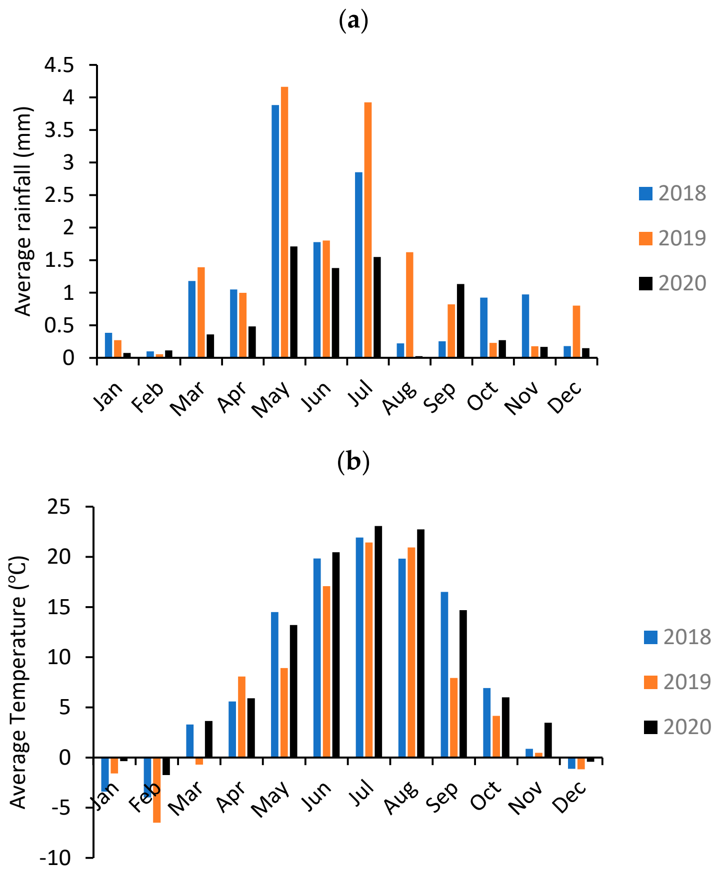

Figure 1. Meteorological data showing monthly average rainfall (**a**) and monthly average air temperature (**b**) for the three growing seasons (2018, 2019, and 2020) at the study sites.

3.4. Plant Growth and Weather Conditions

3.4.1. Rainfall and Air Temperature at the Experimental Site

As shown in Figure 1, average rainfall during the plant growing seasons (May–August) in the first year (2018) and third year (2020) of the study period was significantly lower compared with the second year (2019). The effect of the dry years on the unirrigated rangeland soil was reflected in the lower grass biomass production in 2018 and 2020 compared with the wet year 2019. Average air temperatures were below 0 °C in the months of January and February and started to rise above 10 °C from May in all three years' study periods.

3.4.2. Grass Biomass Productivity

In general, treatment with CC and BC incorporated with manure resulted in greater aboveground grass biomass in all three years' study periods. In the cropping years 2018 and 2019, CC650M and BCM resulted in a significantly greater grass biomass than the control. As shown in Table 5, the control treatment yielded the lowest grass biomass of 99.8 g m^{-2}, and the most significant yield was obtained with CC650M (194.2 g m^{-2}) followed by BCM (188.8 g m^{-2}) in 2018. This was also true in the second year (2019), where CC650M (307.1 g m^{-2}) and BCM (292.6 g m^{-2}) produced significantly greater grass biomass yield compared with the control (216 g m^{-2}). In the third year of the study (2020), only CC650M (198.3 g m^{-2}) produced significantly greater dry grass biomass compared with the control (98.6 g m^{-2}). This significantly greater dry grass biomass in CC650M signifies that CC pyrolyzed at 650 °C co-applied with manure is most suitable to enhance plant growth in degraded rangeland soil. In all three years' study results, BC co-applied with manure also seemed effective for plant growth. This may be associated with the synergistic effects of char materials for enhancing soil properties, and the manure providing essential plant nutrients and increasing soil organic matter. A recent study [48] reported that biochar applied at 10 ton ha^{-1} combined with farmyard manure applied at 5 ton ha^{-1} significantly increased total organic carbon, total nitrogen, CEC of the soil, and available phosphorous in a field experiment on sandy clay–loam soil. Manure contains a greater concentration of essential plant nutrients (N, P, K) compared with CC and BC (Table 3), and that might have contributed to greater grass biomass production obtained with manure-incorporated treatments. Co-application of manure with char materials should provide higher levels of essential plant nutrients, improve the physical, chemical, and biological properties of soil, and hold nutrients and moisture in the soil, resulting in a richer soil microbe population and higher plant productivity. More nitrogen retention was found in soil following biochar application than in the urea-fertilized soil in a pot experiment [56]. In the N-leaching column experiment, the urea-fertilized soil leached out 70% of the urea N in the first day following water treatment, compared with only 39% for the biochar-applied soil, when the N rate was same in both treatments [57].

Table 5. Effects of coal char, biochar, manure alone, and combined application on grass biomass yield (g m^{-2}).

Treatments	Aboveground Dry Grass Biomass (g m^{-2})		
	2018	**2019**	**2020**
Control	99.8 ± 27.6 ^{c}	216.5 ± 17.2 ^{c}	98.6 ± 39.0 ^{b}
M	161.1 ± 74 ^{abc}	247 ± 27 ^{abc}	105.7 ± 67 ^{b}
CC650	100.6 ± 51.1 ^{c}	240.3 ± 45.2 ^{bc}	135.6 ± 91.1 ^{ab}
CC650M	**194.2 ± 57.6 ^{a}**	**307.1 ± 25.6 ^{a}**	**198.3 ± 41.3 ^{a}**
CC750	134.1 ± 33.2 ^{abc}	238.0 ± 34.7 ^{abc}	138.9 ± 78.0 ^{ab}
CC750M	146.0 ± 51.1 ^{abc}	249.8 ± 40.6 ^{abc}	114.0 ± 35.4 ^{b}
CC800	115.2 ± 55.6 ^{bc}	219.1 ± 41.2 ^{c}	144.2 ± 74.6 ^{ab}
CC800M	164.5 ± 50.6 ^{abc}	268.4 ± 37.2 ^{abc}	112.4 ± 47.7 ^{b}
BC	147.1 ± 50.1 ^{abc}	251.0 ± 45.1 ^{abc}	126.0 ± 51.8 ^{ab}
BCM	**188.8 ± 63.5 ^{ab}**	**292.6 ± 55.7 ^{ab}**	150.3 ± 30.6 ^{ab}

Mean weight of aboveground grass biomass (n = 12) with the associated standard errors. Within a column, values not sharing a common letter are significantly different at α = 0.05 in the post-hoc Fisher's LSD test. Values in bold represent statistically significant difference from the control.

Manure mixed with CC and BC could have worked as a composted char product. A study [58] reported that composted BC released fertilizer slowly in the soil. That study also mentioned that composting of BC could provide relaxation time for water molecules to interact with the BC pore surface, thus contributing to the retention of water-dissolved nutrients as water become less mobile within the pore spaces. High application rates (0.5–4% w/w) of biochar significantly increased total nitrogen content in the soil tested after the leaching experiment in the laboratory [59]. This might indicate potential N-use efficiency with the use of char materials on dryland soil. However, further studies are required to confirm the nutrient retention capacity of CC and BC.

Continuous three-year field experiment results indicated that CC performed similarly to BC as they produced comparable dry grass biomass yield (Table 5). Grass biomass productivity was greater in 2019 with all treatments compared with the 2018 and 2020 growing seasons (Table 5). This may be because of the variation in precipitation in the plant growing season at the study site. May, June, July, and August are the main plant-growing months of this study site with suitable air temperature (Figure 1b), and there was more significant rainfall in those months in 2019 compared with the amount of rainfall in the 2018 and 2020 growing seasons (Figure 1a). A study on dryland productivity [60] mentioned the negative effect on aboveground net primary production in dry years and the positive effect on production in wet years. Soil moisture is one of the primary limiting factors for productivity on unirrigated dryland ecosystems.

Among the three types of CC-only treatments, CC750 delivered relatively better results with grass biomass yield of 134.1 g m^{-2}, followed by CC800 and CC650 with

115.2 g m^{-2} and 100.6 g m^{-2}, respectively, in 2018, which were greater yields than the control (99.8 g m^{-2}) for that growing season. However, none of the CC-only treatments produced significantly more grass biomass yield ($p > 0.05$) than the controls (Table 5) in the respective years. The CC- and BC-only treatments performed marginally better than the control in all three years of the study period. However, the difference was not statistically significant ($p > 0.05$). A previous study on BC [61] also revealed low nitrogen availability when BC was applied as a soil amendment in a small-scale experiment. Due to its porous nature, BC can absorb water, air, and soluble nutrients [62]. Similarly, CC may have absorbed some nutrients from the soil at the beginning of the application. Moreover, the char products themselves do not contain the essential plant nutrients. A study [63] reported that it is still unclear whether BC application to soil reduces the requirement for inorganic fertilizers. This study hypothesized that treatments incorporating organic carbon materials would yield more than the control plot. According to the test results, it was observed that manure incorporation with CC and BC generated a significant increase in plant productivity in the degraded rangeland soil.

4. Conclusions

This study demonstrated that use of CC and BC as soil amendments could increase soil organic carbon and CEC in semiarid rangeland soil. At the same time, CC and BC incorporated with manure increased grass biomass production as well as soil OM and CEC. The high surface area and greater pore spaces of CC and BC can retain nutrients supplied from manure, holding soil moisture for extended periods in unirrigated drylands. Therefore, manure co-applied with CC and BC could be beneficial to increase plant productivity and improve soil properties in semiarid soil. As soil amendments, CC and BC provided a comparable grass biomass yield, indicating that both products behave similarly in soil. Coal pyrolyzed at different temperatures (CC650, CC750, and CC800) resulted in similar grass biomass yields. Therefore, it is concluded that the range of pyrolysis temperatures tested did not significantly alter the performance of CC as a soil amendment. However, more in-depth field experiments are required in different soils and crop types to elucidate how CC and BC affect the physical, chemical, and biological properties of soil and therefore influence soil health and plant growth in semiarid rangelands.

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